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FIBER-OPTIC SENSORS FOR VIBRATION AND STRAIN MEASURING - A REVIEW

Vlaknasto-optički senzori za vibraciju i mjerenje naprezanja - pregled

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Summary

This article presents a brief overview of fiber-optic sensors and their development in the past 30 years. The new technologies like FBG or OTDR sensing principles have formed an entirely new generation of sensors. Some of these sensors, depending on their applications and measurands, have been successfully commercialized and they are shown in this article.

Also, a multimode fiber optical sensor that measures vibrations, is presented. Multimode fiber has a relatively large number of modes that travel simultaneously through the fiber and interfere with each other. By applying various forces upon the fiber, mode's way of propagation will be changed, consequently their interference distribution will be changed, therefore generating a different field pattern at the fiber end. Difference in field pattern can be used for obtaining vibration parameters such as the amplitude and the frequency.

Keywords: fiber-optic system, applications, strain sensing, vibration sensing, BOTDR, FBG.

Sažetak

Ovaj članak prikazuje kratak pregled vlaknasto-optičkih senzora i njihov razvoj u proteklih 30 godina. Nove tehnologije kao FBG ili OTDR osjetilni principi, oblikovali su novu generaciju senzora. Neki od ovih senzora, ovisno o svojoj primjeni i mjerama, uspješno su komercijalizirani, pa su prikazani u ovom članku.

Također je prikazan vlaknasti optički sustav senzor koji mjeri vibracije. Multimodalno vlakno ima relativno velik broj načina da simultano putuje vlaknom i interferira jedno s drugim. Primjenjujući različite sile na vlakno, način propagiranja će se promijeniti, pa će se njihova distribucija interferencije promijeniti, stoga generirajući različit uzorak polja na kraju vlakna. Razlika u polju uzorka može se upotrijebiti za dobivanje parametara vibracije kao što su amplituda i frekvencija.

Ključne riječi: vlaknasto-optički sustav, primjena, naprezanje, mjerenje vibracije, BOTDR, FBG

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INTRODUCTION / *Uvod*

The evolution of the fiber-optic sensors started in mid 1970s with the development of the optical telecommunication industry (networks). The progress of the optical communication networks was led by an increasing demand on a communication capacity (bandwidth) that could not been satisfied with the convencional electrical communication networks due to their fundamental limitations (in particular low bandwidth due to low carrier frequency). Because of the slow progress in the beginning in the development of the fiber-optic systems and their high market price, electrical (communication) systems are still used, but they are being pushed and main advantage is given to the fiber-optic systems due to their characteristics like immunity to electromagnetic interference, lightweight, small size, good corrosion resistance, high sensitivity, large bandwidth, an ease in signal transmission, long-term reliability, low power, high dynamic range, high resolution, resistance to high temperatures etc.

With the rapid advent of optical communication networks, the cost of fiber optic sensors has substantially dropped because of the commercially viable key components in fiber optic communications such as light sources and photodetectors. So, the ability of fiber optic sensors to displace traditional sensors for rotation, acceleration, electric and magnetic field measurement, temperature, pressure, acoustics, vibration, linear and angular position, strain, humidity, viscosity, chemical measurements, and a lot of other sensor applications has been enhanced.

One of the most important advantages of fiber optic sensors is their ability to implement distributed sensing, which significantly enhances the commercial viability of fiber optic sensors. They are capable to integrate a large number of passive optic sensors or sensing regions within a single fiber, which provides a lightweight, compact-size, low cost approach. By taking advantage of this multiplexing capability, not only the magnitude of a physical parameter or measurand can be monitored, but also its variation along the length of the fiber can be measured.

Therefore, this distributed sensing possibility, which not only makes fiber optic sensors more cost-effective, opens many important applications such as monitoring the performance of optic networks and fatigues of critical structures (Structural Health Monitoring) such as bridges, dams, mines, marine vehicles, aircrafts etc. Fiber-optic sensor technology for "smart" structure applications provides one of the most desirable attributes, an ability to embed the sensor within the structural material. Embedding procedure makes it possible to measure parameters at locations not accessible to ordinary sensors, which must be attached to the surface. The embedded sensor is protected from damage and isolated from external environmental effects by the structure itself. In order for a sensor to be successfully embedded in a composite or metal part, it must withstand the mechanical and thermal stresses experienced when the considered part is formed. Therefore, sensor packaging is of great importance [1]. Curing of composites generally requires a combination of elevated temperature and applied pressure. During the casting of metals of structural interest, the sensor will experience high temperatures combined with severe compressional stresses as the part cools to room temperature. Optical fibres are fragile and are subjected to breakage during packaging, transportation, especially during installation to the host structures. In addition, the thermal expansion coefficient of the sensor packaging should be approximately equal to that of the host structure to avoid possible damage between the interfaces.

There are two types of distributed fiber optic sensors: intrinsic distributed fiber optic sensors and quasi-distributed fiber optic sensors. For the intrinsic distributed fiber optic sensors, a single measurand can be monitored continuously over the path of the fiber. The major intrinsic distributed fiber optic sensor methodology is optical time-domain reflectometry (OTDR), either based on Rayleight or Brillouin scattering. However, in some cases truly distributed sensing is difficult to realize, and so the quasi-distributed fiber optic sensors are used. In this case, the measurand is not monitored continuously along the fiber path, but at a finite number of locations by multiplexing point fiber optic sensors. An example of quasi-distributed fiber optic sensor is a Fiber-Bragg Grating sensor, where each grating measures the given parameter at its point of space.

DISTRIBUTED STRAIN SENSING / *Distribuirano mjerenje naprezanja*

Distributed Strain Sensing from Composite Materials based on the Brillouin Scattering / *Distribuirano mjerenje naprezanja od kompozitnih materijala temeljenih na Brillouin Scattering*

Fiber-optic distributed sensors that return a value of the measurand as a function of linear position along an optical fiber can be used for sensing elements of structural health monitoring (SHM) system. There are three types of light scattering in optical fibers that can be used in distributed sensing: Rayleigh, Raman and Brillouin scattering. In this paper, we will focus on the Brillouin scattering. The inelastic scattering process of Brillouin light scattering

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is in principle the same as Raman scattering (Raman scattering is an inelastic scattering of a photon). When light interact with an atom or molecule, most photons are elastically scattered. This scattering is responsible for the blue color of the sky; it increases with the fourth power of the frequency and is more effective at short wavelengths). When an optical pulse is launched into an optical fiber, stimulated Brillouin scattering occurs from acoustic vibrations stimulated in the optical fiber. The acoustic vibrations cause a counterpropagating wave that drains energy away from forward-moving input pulse. To satisfy the requirement of energy conservation, there is a frequency shift between the original light pulse frequency and the Brillouin scattering wave, which, in general, is in the order of tens of GHz. The spectrum of the scattered light is characterized by three parameters, as shown in Figure 1: the Brillouin frequency shift v_b, the Brillouin linewidth Δv_b, and the Brillouin gain coefficient g_b. The Brillouin frequency shift v_b is given by [3]:

$$v_b = \frac{2nV_a}{\lambda} \tag{1}$$

where n is the fiber core refractive index, V_a is the acoustic velocity and the λ is the light wavelength. The shift is about 11GHz at a wavelength of 1550 nm. It was detected that the Brillouin frequency shift in silica fibers varies with longitudinal strain present in a fiber and its dependency on strain is given by:

$$v_b(z) = v_{b0} + M\varepsilon(z) \tag{2}$$

where v_{b0} is the Brillouin frequency shift when no strain is present, M is the proportionality constant, and $\varepsilon(z)$ is the strain value at a position z along the sensing fiber. The proportional constant M is 49.3 GHz at 1550 nm.

Since the frequency shift of a Brillouin gain spectrum is sensitive to the temperature and strain, it becomes a very useful effect to build fiber optic sensors. In particular, the frequency shift depends on the magnitude of the longitudinal strain, which comes from the fact that, under different longitudinal strain conditions, the acoustic wave frequency induced by the photon is different. Thus, the longitudinal strain distribution can be measured by measuring the Brillouin scattering effect.

Brillouin spectra along a sensing fiber can be obtained from a BOTDR system and the system configuration is shown in Figure 2. A continuous coherent lightwave with the frequency (υ) is divided into probe and reference lightwaves. The probe lightwave is modulated into a pulse by an acousto-optic pulse modulator (AO1) and launched into the frequency translation ring circuit, which contains an erbium-doped fiber amplifier (EDFA) and an acousto-optic frequency shifter (AO2). After a certain number of circular propagations, a probe pulse can be obtained with a frequency shift v_s approximately equal to the Brillouin frequency shift v_b. Then the probe pulse power is amplified by an EDFA and launched into a sensing fiber. The spontaneous Brillouin backscattering lightwave in the sensing fiber is directed into a heterodyne receiver, in which the reference lightwave is used as an optical local oscillation. Since the frequency of the Brillouin scattered pulse is downconverted by Brillouin scattering and returns with frequency that is approximately the same as the reference lightwave, the heterodyne beat frequency, v_s-v_b, can be reduced to be less than 100 MHz, which is in typical effective frequency band of a conventional heterodyne receiver. Brillouin spectrum can be obtained by changing the probe frequency shift v_s as shown in Figure 3.

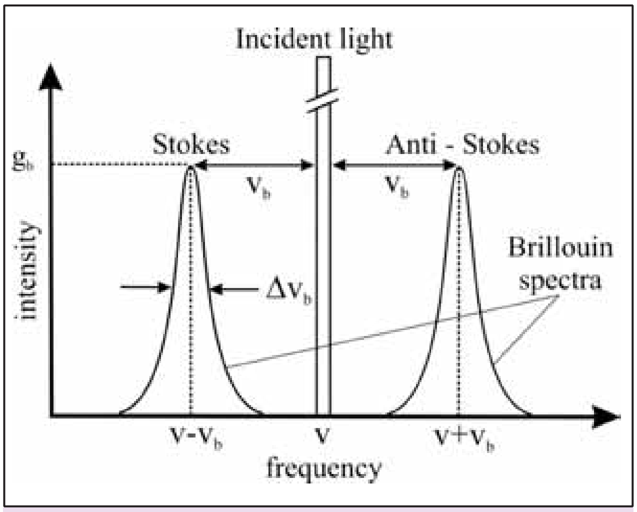

Figure 1. Brillouin spectra
Slika 1. Brillouin spektar

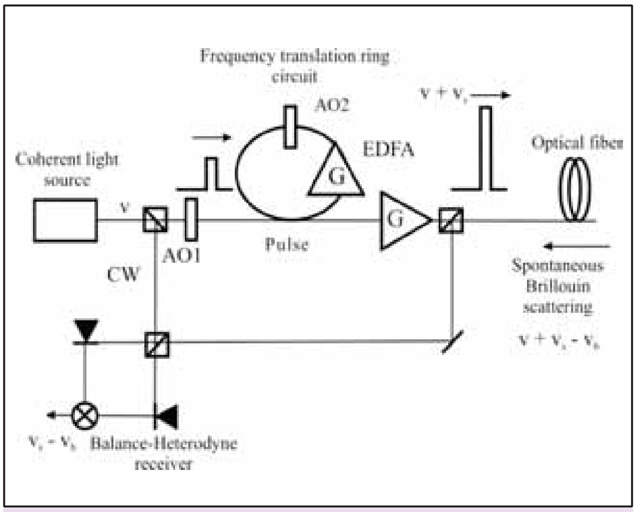

Figure 2. Optical configuration of BOTDR
Slika 2. Optička konfiguracija BOTDR-a

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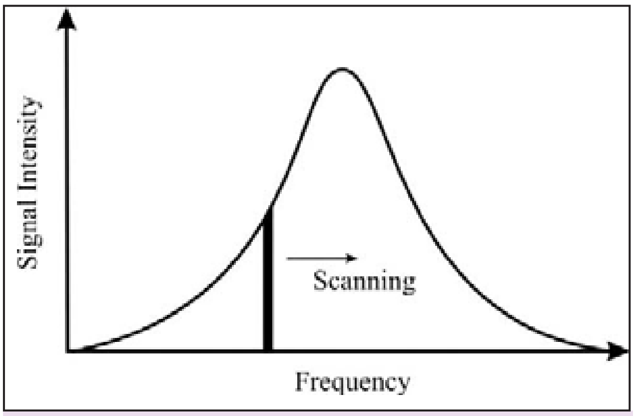

Figure 3. Brillouin spectrum measurement
Slika 3. Mjerenje Brillouin spektra

The Brillouin spectrum can be described using the Lorentzian with full width at half maximum (FWHM) Δv_b, (i.e. Brillouin linewidth), center frequency v_b, (i.e. Brillouin frequency shift), and peak gain g_b (i.e. Brillouin scattering coefficient). When strain ε(z) is applied to the sensing fiber uniformly along its length, the Brillouin gain spectrum in the fiber is given by:

$$g(v_s, v_b) = \frac{g_b}{1 + 4(v_s - v_b)^2 / \Delta v_{b0}^2} \tag{3}$$

where Δv_{b0} is the Brillouin linewidth for uniform fibers. When the strain varies along the sensing fiber, the actually measured Brillouin spectrum, ignoring the fiber attenuation, is given by:

$$\bar{g}(v_s, z) = \frac{1}{L} \int_{z-L/2}^{z+L/2} g(v_s, v_b(\xi)) d\xi \tag{4}$$

where *L* is defined as the spatial resolution of the BOTDR system. If the strain along the sensing fiber is not distributed uniformly within the length of the spatial resolution, the actually measured Brillouin spectrum will be deformed in conforming with the Lorentzian shape. The spatial resolution δz of BOTDR usually depends on the incident pulse width *W*, as in case of conventional OTDR, and is determined by:

$$\delta z = \frac{vW}{2}, \tag{5}$$

where *v* is the velocity of light in optical fibers. Although this equation shows that the narrowing of the pulse improves the spatial resolution, the shorter pulses will decrease the frequency resolution of the measurement, system, i.e. the the accuracy of strain measurements will be reduced.

Strain measurement by BOTDR is nearly close to the strain averaged by the length of the spatial resolution. Therefore, it is difficult to detect inhomogeneous strain distributed within 1m along a fiber because the typical spatial resolution is longer then than 1m. When BOTDR is used to detect a damage or deformation in a structure leading to local changes in the strain distributions, the higher spatial resolution would be required.

Strain Sensing from Composite Materials Based on BOTDR / *Mjerenje naprezanja kompozitnih materijala temeljenih na BOTDR*

The desired strain detection method (shown in Figure 2.), based on a fact that the profile of the Brillouin spectrum changes depending on strain distributions, is a new method of strain sensing for composite structures, and it was used for strain measurements and damage detections of a yacht's structure[3]. The yacht was an International America's Cup Class (IACC) yacht made of carbon fiber-reinforced plastics (CFRP) and it was equipped with fiber-optic sensors. The main goal was to measure transverse strain of the structure subjected to a test load. In addition, strain distributions of the structure were calculated by finite element analysis (FEA). Figure 4. shows the sensor location in the yacht and the loading condition. The sensing fiber was fixed along the bonded joint between the hull and the bulkhead supporting the mast. The test load is comprised of two forces: one is the tensile force of about 15 tons by each shroud and another is the pushing force of about 30 tons by the mast. A shroud is like a wire that helps to support the mast by running from the top of the mast to the side of the yacht.

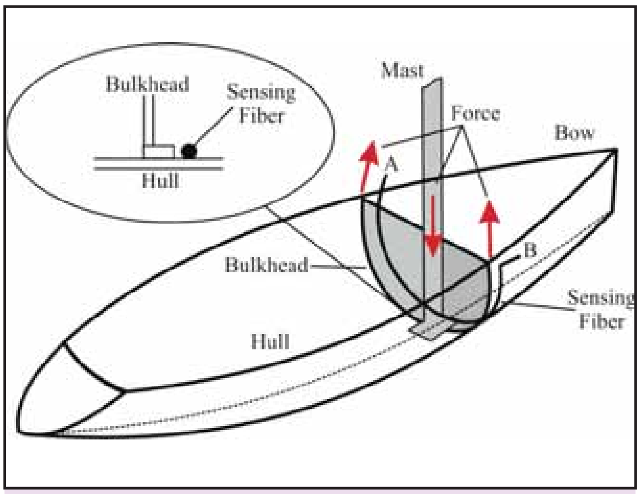

Figure 4. Sensor location in the yacht and the loading condition in measurements.
Slika 4. Lokacija senzora na jahti i uvjeti krcanja u mjerama

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It can be seen that, calculated by FEA, there is a large deformation below the mast. The strain distributions along the sensing fiber, measured by the BOTDR system and calculated by FEA, are shown in Figure 5. The matching between the measured and calculated results is excellent although strain is varying within the spatial resolution. It can be seen that BOTDR is useful measurement method to effectively find overall deformation of a structure.

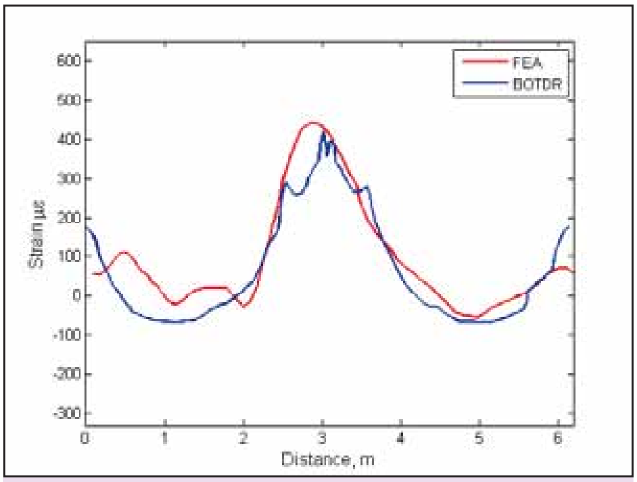

Figure 5. Measured and estimated strain distributions along the sensing fiber

Slika 5. Izmjereni i procjenjeni raspored naprezanja duž osjetilnog vlakna

Strain Sensing Based on a FBG / *Mjerenje naprezanja na temelju FBG*

Fiber Bragg gratings (FBG) have been a subject of many researches since they were discovered. FBGs are periodic structures that are imprinted directly into the core of glass optical fibers by powerful ultraviolet radiation (UV). Such structures consist of a periodically varying refractive index over typically several millimeters of the fiber core (Figure 6.) [4]. The specific characteristic of FBGs for sensing applications is that their periodicity causes them to act as wavelength sensitive reflectors.

During the imprinting process, the intensity of the UV illumination is made to occur in a periodic fashion along the fiber core. At a sufficiently high power level, local defects are created within the core, which then give rise to a periodic change in the local refractive index. The changes of index created in this way are relatively permanent and are sensitive to a number of physical parameters—notable examples being pressure, temperature and vibration. Thus, by monitoring the resultant changes in reflected wavelength, FBGs can be used in a variety of sensing applications to measure physical quantities such as strain, temperature, pressure, ultrasound, high magnetic field, force and vibration. In FBG the Bragg wavelength λ_B, or the wavelength of the light that is reflected, is given by

$$\lambda_B = 2n_{eff}\Lambda, \qquad (6)$$

where n_{eff} is the effective refractive index of the fiber core and Λ is the grating period [5]. In Eq. (6) it can be seen that the Bragg wavelength is changed with a change in the grating period or the effective refractive index.

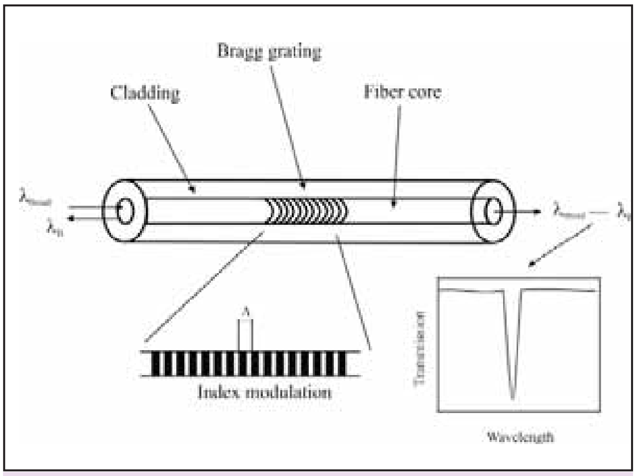

Figure 6. Illustration of a uniform fiber Bragg grating and its wavelength selective reflection property

Slika 6. Ilustracija uniformiranog vlakna Bragg i njegova karakteristika selektivne reflekcije duljine vala

FBGs were initially reserved primarily for academic research, mostly because of fabrication techniques. External writing technique has changed that and has led to wide acceptance of fiber gratings in communications and later in sensor applications. Nowadays, there are several techniques for writing refraction index changes, each with some advantages and disadvantages, but all of them give us the ability to control the Bragg wavelength – wavelength at which the magnitude of reflection coefficient has maximum.

FBG Sensor / *FBG Sensor*

Optical sensors based on FBGs have a number of distinguishing advantages. They can give absolute measurement that is insensitive to power fluctuations of the source, they can be multiplexed using techniques developed for communication purposes, and cost of producing FBGs can be quite low if quantities are high enough [6]. Typical sensor device (Figure 7.) consists of a optical source with sufficiently broad spectrum, FBG and a spectral analyser. All physical quantities that can

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be measured affect the central Bragg wavelength of fiber. Change of the Bragg wavelength is easily detectable with optical spectral analyzer (OSA), under condition that it offers sufficient resolution. All used components are quite cheap except, of course, the spectral analyser. Its price heavily affects widespread of use of such a sensor. Ideal source for this type of sensor would offer completely linear spectrum in range of interest – usually around 4 nm, depending on temperature or strain ranges that are planned to measure. Typical realization has one large drawback –both strain and temperature change the central Bragg wavelength, so if we want to measure only one physical value other must be controlled or compensated. Separating these sensitivities can make quite a problem and can raise cost of the whole system. The simplest method is the one with referent FBG placed in strain-free environment (Figure 8). Referent FBG is then used for temperature measurements and compensation of results obtained by the second FBG.

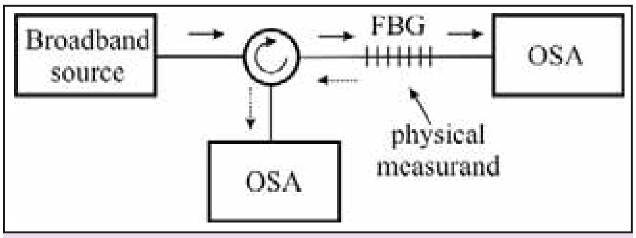

Figure 7. Typical optical sensor based on FBG. Wavelength shift can be measured on transmission or spectrum reflection of FBG

Slika 7. Tipični optički senzori temeljeni na FBG. Pomicanje duljine vala može se mjeriti transmisijom ili refleksijom spektruma FBG

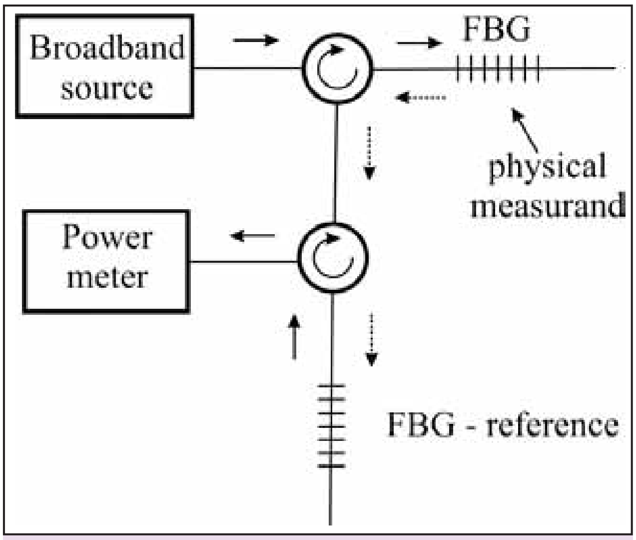

Figure 8. Optical sensor based on two FBGs

Slika 8. Optički senzor temeljen na dva FBG-a

Measured characteristics of used FBGs are given in Figure 9. If both FBGs are under no strain condition (they have to be as similar as possible) and under same temperature, power meter will give maximum value as reflection spectrums of both gratings overlap. In case that one grating comes under strain its spectrum will shift toward longer wavelengths and overlapping will decrease, decreasing the measured power at the power meter.

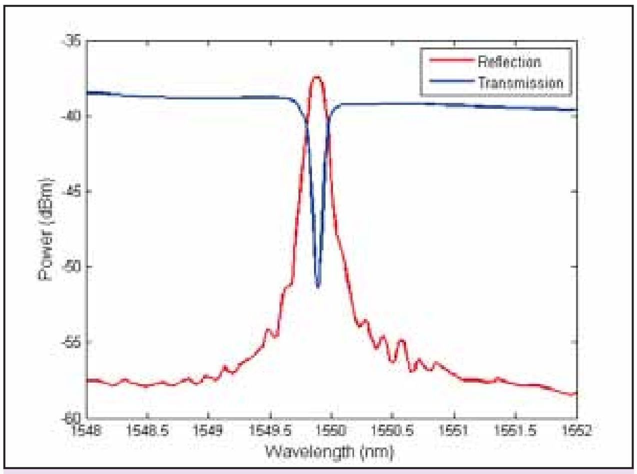

Figure 9. Measured spectrum of used FBG.

Slika 9. Izmjereni spektrum korištenog FBG-a

Heaving two almost identical FBGs allows us to easily thermally compensate the whole system. The only thing that has to be done is to place two gratings close enough so that they are under the same temperature conditions. Under those circumstances reflection spectrum of the second grating will follow spectrum of the first one that is used for strain sensing and only strain (not temperatures) will have effect on reading of the power meter. This approach gives the best results in rather narrow area as grating that, in this case, is used for amplitude modulation has quite narrow spectrum. Depending on situation this can be enough – temperature changes in order of 50 °C can be measured or microstrain of around 500 (which, for typical fiber, translates in force of around 0,5 N). Better precision is obtained with smaller temperature, or strain changes. Greater forces can be measured by using couple of optical fibers put in parallel without significant increase of the price. Note that other fibers can be plane fibers, i.e. without gratings imprinted in them. Range for force measurement can easily be broadened with this approach, but the price that is paid is lowering of precision.

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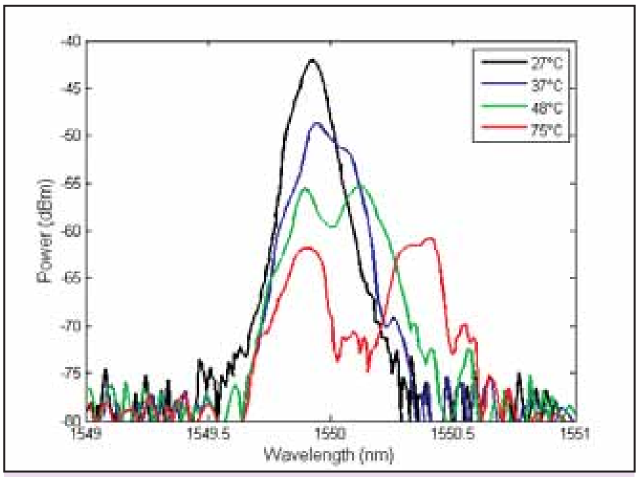

Figure 10. Changes in output spectrum when one FBG is heated

Slika 10. Promjene u izlaznom spectrum kada je jedan FBG zagrijan

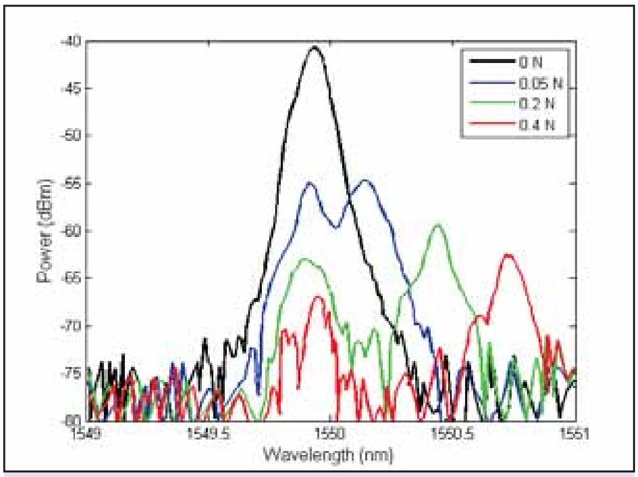

Figure 11. Changes in output spectrum when one FBG is put under strain

Slika 11. Promjene u izlaznom spektrumu kada je jedan FBG pod naporom

VIBRATION SENSING / *Mjerenje vibracije*

Measuring Vibrations with a Multimode Fiber Optical Sensor / *Mjerenje vibracija multimodalnim optičkim vlaknastim senzorom*

Multimode fiber, as a result of its large core diameter, has a relatively large number of modes that travel simultaneously through the fiber. Each mode travels with its own group velocity and propagation constant, but interferes with other modes as they share the same medium. There are around 500 modes in a typical multimode fiber [7]. The speckle pattern inside the fiber can be detected by projecting it from the fiber ending upon a screen. It consists of large number of small areas with different intensities of light (Fig. 12). This is nice visual proof that light indeed travels in many modes throughout fiber if the normalized frequency exceeds 2,405. Speckle pattern changes slowly in time, but its total summed intensity remains the same. That can be expressed by the following equation

$$I_T = \sum_{i=1}^{N} I_i \qquad (7)$$

where I_T is the total intensity, I_i is the intensity of each point (small area) in the speckle pattern and N is the number of areas. In reality that is the number of photo detectors inside a CCD camera.

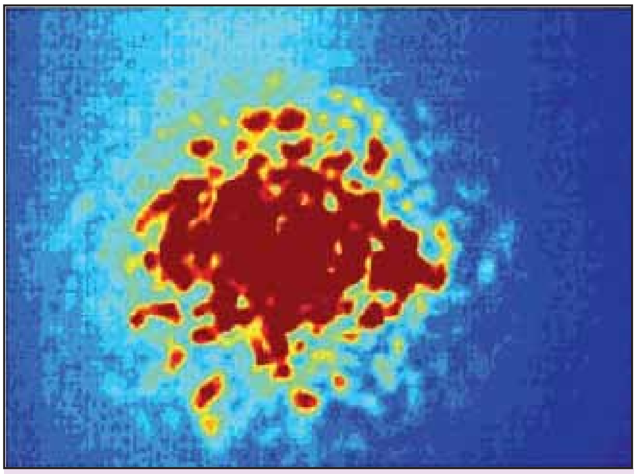

Figure 12. Speckle pattern (distribution of light intensities)

Slika 12. Točkasti uzorak (distribucija intenziteta svjetla)

If the fiber is exposed to vibrations, distribution and the intensity of these points begin to change in correlation with the vibration force. Same effect can be seen with stretching and bending of multimode optical fiber. The intensity of a single speckle can be expressed as function of the force ($F(t)$) perturbing the fiber by the following expression:

$$I_i = A_i\{1 + B_i[\cos(\delta_i) - F(t)\varphi\sin(\delta_i)]\}, \qquad (8)$$

have A_i is the result of mode self-interaction, and the next two terms represent the mode-mode interaction, the first one (B_i) accounting for the steady state, and the second one ϕ_i, signify the modification of the mode-

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mode interaction if the system is perturbed. Signal output, in which the absolute value of changes in the intensity pattern is summed up, is given by:

$$\Delta I_r = \left[\sum_{i=1}^{N} |C_i \sin(\delta_i)| \right] \left| \frac{dF(t)}{dt} \right| \quad (9)$$

By applying various forces upon the fiber, the way how the modes propagate is changed and therefore their interference distribution is also changed which results in different field pattern at the fiber end. While calculating exact changes of propagation parameters for each mode (resulting from applying the force) is an extremely complex task, good results can be obtained only by studying changes in speckle pattern at the fiber end. From these changes, it is quite easy to detect not only vibrations , but also to obtain information about the vibration parameters such as the amplitude and the frequency. A sensor system used in this method can be built using cheap and widely available components. Figure 13. shows basic block scheme of the system used to record and analyze the changes in the distribution of the light caused by vibrations of fiber [8].

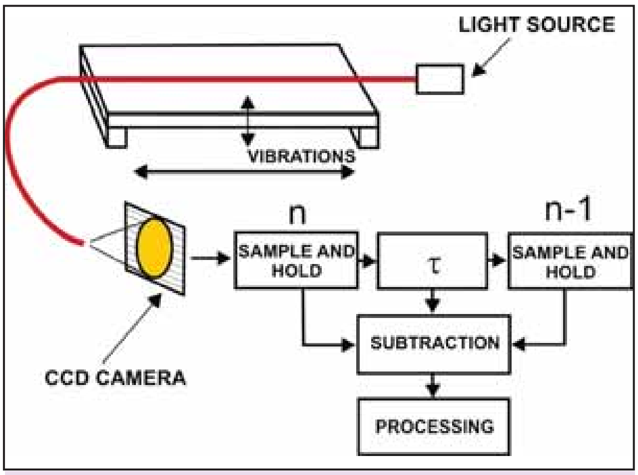

Figure 13. Basic sensor system scheme for detecting vibrations.

Slika 13. Bazični sustav sheme senzora za detektiranje vibracija

The signal coming from the source (laser operating in visible spectrum) travels through multimode fiber. Output signal from the fiber's end is projected on the screen, and is recorded by a simple CCD camera used only for demonstration of the principle. Since the data is recorded in video signal mode, it is first broken down to frames (25 per second) and then analyzed as a set of sequential frames that each represents a matrix of speckle pattern points intensities in time (Figures 14-17). Different analysis steps of the video frames included loading image in memory, calculating total intensities, differences between images, and extracting the amplitude of vibrations. Multimode fiber is exposed to mechanical vibrations in one point. If multipoint vibrations are present, some difficulties arise as it is possible to analyze only image at fiber's end where influences from all vibration points interfere. Maximum detectable frequency is limited via Nyquist criteria by sample frequency of detector – in this case web camera. As it's sample frequency was around 25 frames per second, it was possible to measure vibrations with frequencies up to approximately 12 Hz [9]. By constructing custom CCD sensor, higher frequencies can be detected, so some tradeoffs between processing requirements and maximum detectable frequency is present.

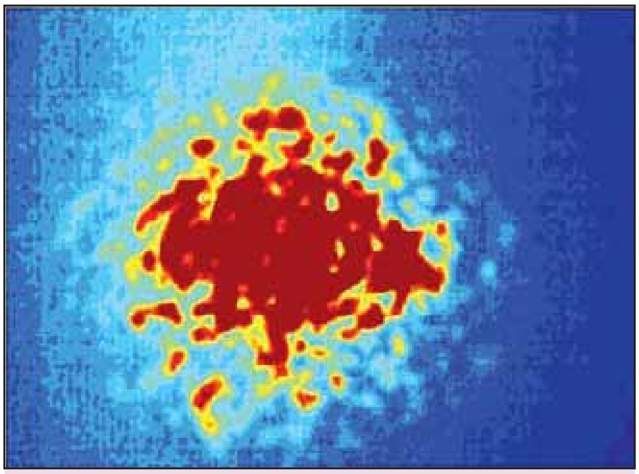

Figure 14. A single frame extracted from the video signal

Slika 14. Jedini okvir izveden iz video signala

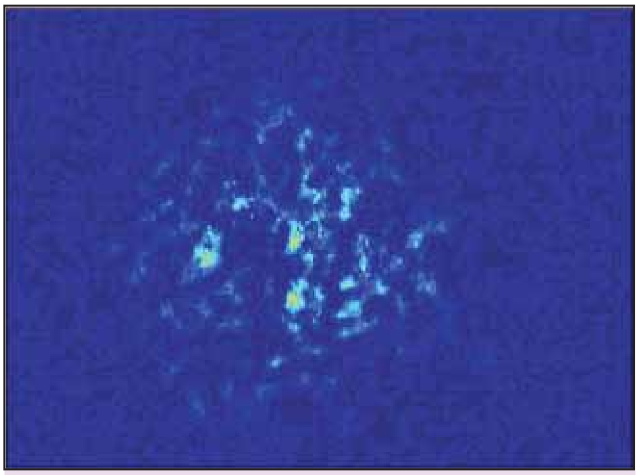

Figure 15. A difference picture between two sequential frames when the vibrations are present

Slika 15. Slika razlike među dva sekvencijska okvira kada su prisutne vibracije

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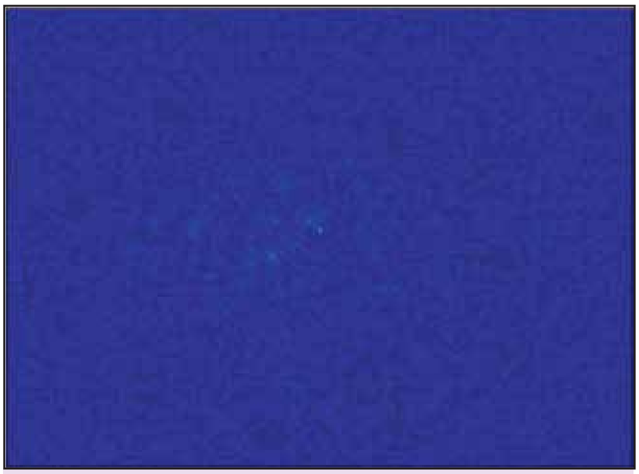

Figure 16. A difference picture between two sequential frames when the vibrations are not present.

Slika 16. Slika razlike među dva sekvencijska okvira kada nisu prisutne vibracije

CONCLUSION / *Zaključak*

In this paper a brief description of fiber optic sensors and their applications have been reviewed. Soon after the development of optical fibers for communication application, it was realized that they could also be used for sensing applications. Fiber optic sensors have developed substantially from the experimental stage to practical applications. The new sensing technologies like FBG or OTDR sensing principles have formed an entirely new generation of sensors offering many important measurement opportunities and great potential for diverse applications. As examples the strain sensor systems based on these sensing principles are described. Such sensor systems can be used in wide range of applications–strain monitoring in buildings, bridges, yachts, etc.

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